Data Assimilation and Model Evaluation Experiment: North Atlantic Basin

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In addition to the Principal Investigators listed above, technical personnel have also included Mr. Mike Crowley (remote sensing), Dr. Julia Levin (Kalman filters), and Drs. Kate Hedstrom and Hernan Arango (SCRUM/ROMS specialists).

LONG-TERM GOALS

Our long-term goal has been the realization of an improved mesoscale prediction capability in the North Atlantic Basin through the development of advanced prognostic modeling systems, the preparation of remotely acquired and *in situ* datasets, and their joint use for validation and data assimilation studies.

SCIENTIFIC/TECHNICAL OBJECTIVES

We seek to build and to apply more accurate and efficient models of the basin-scale ocean circulation, including the adjacent continental shelves and marginal seas. Modeling objectives include: (1) evaluation of the prognostic realism of our newest terrain-following coordinate model (ROMS); (2) the implementation of a new generation of basin-scale ocean circulation models based on the spectral finite element technique, and the assessment of its performance relative to ROMS; and (3) assimilation of North Atlantic datasets (*e.g.*, sea surface height) into the ROMS model using the reduced-state Kalman filter. Our concurrent observational objective has been: (4) the finalization and distribution of North Atlantic altimeter, sea surface temperature, and CTD/XBT datasets for use by DAMEE participants in assimilation and model validation.

APPROACH

Our primary modeling tool has been the Regional Ocean Modeling System (ROMS) – a non-linear terrain-following ocean circulation model recently developed in partnership with UCLA (Prof. James McWilliams and colleagues). It is a descendent of the SPEM and SCRUM family of models, but with significant enhancements in computational performance, particularly on SMMP systems, and in the areas of time-stepping and advection algorithms.

For comparison with this more traditional model class, we have developed a new oceanic general circulation model which utilizes a high-order Galerkin (finite element) formulation. The resulting

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model algorithms combine geometrical flexibility with rapid convergence, low truncation error and high accuracy (Haidvogel *et al.*, 1997).

In the area of data assimilation, our approach is based on the reduced-state linearized Kalman filter algorithm developed by Fukumori and Malanotte-Rizzoli (1995). The reduced-state construction is based on a representation in empirical orthogonal functions (EOF's).

For dataset synthesis, our approach has been to acquire data from the TOPEX altimeter, two versions of the AVHRR-derived SST, and archived XBT/CTDs; to quality control and process these datasets as required; and to compare the resulting datasets with previous analyses where available.

TASKS COMPLETED: MODELING

Implementation, execution, and evaluation of two independent sequences of North Atlantic Basin simulations has been pursued. The two models in use are the Regional Ocean Modeling System (ROMS) and the Spectral Element Ocean Model (SEOM). The former, a finite-difference-based model developed in part with ONR support (N00014-95-1-0457), has been redesigned for efficient performance on available parallel computer architectures. The latter, a new model using unstructured horizontal grids and higher-order h-p-type finite elements, is used to assess the potential advantages of these more novel methods.

We have configured ROMS for coarse-resolution and marginally eddy-resolving studies in two separate domains. The former corresponds to the consensus DAMEE domain (6°N to 47°N); the latter extends from 30°S to 65°N, and has been chosen to more effectively limit the influences of open boundary conditions. Three average horizontal resolutions have been explored: 0.75, 0.5 and 0.3 degrees. Multi-year sensitivity studies have now been conducted at all three resolutions, with the intent of understanding the mutual effects of: (a) topographic smoothing, (b) non-linear terrain-following coordinates, (c) advection algorithm, (d) subgridscale closure, and (e) treatment of lateral boundaries.

A reduced-state Kalman filter has also been successfully implemented for SCRUM/ROMS. A series of simulations has been performed to explore alternative state-reduction strategies, and the choice of model error statistics and linearization. To do so, twin experiments in the North Atlantic Basin were performed in which sea surface height at every other grid point is assimilated every 3 days for a year. The steady Kalman gain matrix is computed every month of the simulation using the doubling algorithm of Fukumori and Malanotte-Rizzoli; the state space is very coarse and consists of 25 amplitudes only (compared to several hundred thousands of unknowns in the full model state).

The shallow water version of SEOM (Iskandarani *et al.*, 1994) has now been extended to three spatial dimensions. Two alternative forms of 3D SEOM are currently available: a first based upon a layered vertical representation, and a second which solves the continuously stratified, hydrostatic primitive equations. The former of these 3D versions is not in active use for DAMEE–NAB, though it is being applied to coupled basin-scale/coastal circulation studies in support of U.S. GLOBEC programs in both Georges Bank and the Northeast Pacific. The latter has recently been extended to incorporate the KPP mixed layer model of Large *et al.* (1994), and to allow two-way communication between finite element models of differing Galerkin bases (Levin *et al.*, 1998). The SEOM model therefore offers the first unified treatment of multi-scale ocean modeling, including unstructured grids and/or two-way grid nesting.

TASKS COMPLETED: OBSERVATIONS

The high-resolution (9 km) Pathfinder SST imagery was extracted for the entire Atlantic Ocean. Cloud removal algorithms rate individual pixels as Level 3 (best) through Level 1 (worst). Both warmest pixels and patched composites were constructed using only ascending or only descending passes for only Level 3 data and again for Level 2 and 3 data. All composites therefore were constructed using only ascending or only descending passes.

The IMCS AVHRR data was reprocessed using Pathfinder-like algorithms but without the climatology test to provide 1 km resolution data for the Gulf Stream. Level 2 and 3 patched composites were constructed and the Gulf Stream North Walls digitized every 5 days. Means, standard deviations and extremes were calculated.

Archived XBT/CTD data for 1993 was acquired from NODC. Individual profiles were quality controlled and segmented into daily files. Repeated lines were identified and sections plotted. Matlab interactive software to compare individual isotherms with climatology or model outputs was developed and included with the data.

Previously processed TOPEX altimetry for the Gulf Stream region was added to the dataset. The paper discussing this dataset is now being revised for resubmittal. TOPEX data for the full Atlantic will be provided by NRL.

All of our DAMEE datasets are now described on our website and available via anonymous ftp.

RESULTS: MODELING

Though the degree of realism of the ROMS simulations shows significant sensitivity to *all* of the model-related issues mentioned above, we find that the greatest degree of model improvement is associated with the repositioning of the model boundaries to 30°S and 65°N. Even at lower overall resolution (0.75 degree), the larger domain model produces considerably more realistic indices of basin-scale circulation (*e.g.*, location of the Gulf Stream front, intensity of the Deep Western Boundary Current, and deep water formation rates) than does the small domain at the target resolution of 0.5 degree. A manuscript describing the evaluation of the ROMS simulations has been submitted for publication in the DAMEE–NAB special issue (Haidvogel *et al.*, 1998).

Preliminary twin experiments with assimilation of sea surface height using the reduced-state Kalman filter have been conducted. The K-filter is shown to reduce errors in the ocean hindcast for all prognostic variables except salinity. These effects, as well as extension to multi-dataset assimilation, are ongoing.

The past year has seen extensive intercomparison of the continuously stratified SEOM model with several more traditional circulation models including the Miami Isopycnic Coordinate Model (MICOM), the GFDL Modular Ocean Model (MOM), and SCRUM/ROMS. The basis for this comparison has been a set of analytic and semi-analytic test problems which we have been collecting and refining for some time. Tests problems in this suite include the propagation of a non-linear Rossby soliton, flow around a tall seamount, adjustment of a gravitationally unstable density front, boundary currents along an inclined western boundary, and wind-driven flow over a steep coastal canyon. An extensive summary of these tests will shortly become available as part of a book-length summary of numerical ocean circulation modeling (Haidvogel and Beckmann, 1999). The 3D version of SEOM is presently being run in a head-to-head comparison with ROMS in the 0.5-degree North Atlantic configuration.

RESULTS: OBSERVATIONS

The differences between day and night images is larger than the differences between subsequent days or subsequent nights. Ascending passes therefore were not combined with descending. The climatology test required for a Level 3 pixel quality rating often removes strong fronts like the Gulf Stream. Level 3 warmest pixel composites are the least likely to be contaminated by clouds, but may miss these important features. Level 2 and 3 patched composites often provide the best view of the Gulf Stream, so this method was used with the 1 km resolution IMCS imagery to define the north walls. The highest quality data for the north wall analysis occurred in the middle half of the year (April-September).

Comparisons of TOPEX-derived Gulf Stream axes with AVHRR-derived north walls from individual concurrent satellite overpasses are similar to previous comparisons of GEOSAT altimetry with AVHRR imagery. The average offset was 17.9 km for TOPEX and 17.3 km for GEOSAT, with the strongest trend being an increase in the offset with anticyclonic curvature and a decrease with cyclonic. Comparisons of the mean path of the Gulf Stream derived from AVHRR and TOPEX for 1993 reveal important differences associated with the different sampling patterns of each satellite. The AVHRR mean path east of 60W has much larger meanders than the TOPEX path because the TOPEX repeat tracks do not adequately sample this region. The AVHRR images are weighted more by the summer locations whereas the TOPEX altimeter is year-round. The extremes are especially different, since one of the satellites may observe an extreme event that is totally missed by the other.

IMPACTS/APPLICATIONS

The Spectral Element Ocean Model offers the first unified treatment of multi-scale (*e.g.*, coupled coastal/deep ocean) modeling. Coupled simulations of the North Atlantic / Georges Bank regions and the North Pacific / California Current System are underway.

Pathfinder cloud detection algorithms would be more useful if flags were available for each individual test rather than being broadly grouped into quality Levels 1, 2 or 3. Model comparisons with mean Gulf Stream paths derived from TOPEX or AVHRR should take into account the specifics of each satellite's sampling pattern.

TRANSITIONS

Satellite cloud detection algorithms and compositing techniques developed in DAMEE are now being applied and tested in coastal waters for the ONR-sponsored Coastal Ocean Modeling and Observation Program (COMOP) at Rutgers. Software to quality control XBT/CTD data has similarly been reconfigured for shallow water use as part of the COMOP real-time experiments. Both the ROMS and SEOM models are being used extensively in other ONR-, NSF-, NOPP-, and NOAA-supported projects.

RELATED PROJECTS

The basin-scale modeling capability being implemented and tested under DAMEE/NAB will be used to provide the basin-scale context and coupling to two regional coastal observation/modeling programs. The first, the Rutgers University Coastal Ocean Modeling and Observation Program (COMOP), has as its general objective the understanding and real-time modeling of sediment transport and upwelling frontal dynamics in the New York Bight. The COMOP studies are jointly

funded by ONR/NOMP and NOAA/NURP. The second involve the establishment of a coupled coastal/ basin-scale modeling capability for Georges Bank. These latter studies are funded by NSF. The SEOM model developed under this project also is being used to study sediment transport in the Newark Bay in a New Jersey sponsored project.

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